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MEAN WINDS AND TIDAL COMPONENTS AT THE EQUATOR DURING COUNTER ELECTROJET EVENTS

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The first observations of mean winds and the behavior of amplitudes and phases of diurnal, semi-diurnal and ter-diurnal components measured with a meteor wind radar located at Trivandrum (Geog. Lat. 8.5°, Geog. Long. 77°E, Dip - 0.5°N) during counter electrojet events identified in the horizontal component of the earths's magnetic field in the January and June months of 1987 are described. The mean zonal winds in the altitude region of 90-105 km are in general westward during counter electrojet events of January 1987 and between 80 and 90 km during June. The amplitudes and phases of tidal components on the counter eletrojet days are found to be substantially different from those on the no-counter electrojet days.

VENTOS MÉDIOS E COMPONENTES DE MARÉS NO EQUADOR DURANTE EVENTOS DE ELETROJATO REVERSO *Descrevem-se as primeiras observações de ventos médios observados com radar meteórico. Consideram-se as componentes de períodos 1, 2 e 3, amplitudes e fases, na localidade de Trivandrum (8,5ºN, 77ºE, Dip -0,5ºN), durante eventos de Eletrojato reverso identificados através da componente horizontal do campo magnético, para janeiro e junho de 1987. Os ventos médios zonais na altura de 90 a 105 km são em geral de leste para oeste durante os eventos de Eletrojato reverso em janeiro de 1987, e na faixa de 80 a 90 km para junho. As amplitudes e fases dos componentes de marés nos dias de Eletrojato reverso são muito diferentes daqueles para dias normais.*

INTRODUCTION

The equatorial Electrojet (EEJ) is an enhanced eastward (westward) current in the E region (90-120 km) during daytime (nighttime) near the magnetic equator. The existence of such an intense current system was proposed by Chapman (1951) to account for the abnormal enhancement of the quiet Solar (S_q) daily variation in the horizontal component (H) of the earth's magnetic field at equatorial latitudes in all longitude sectors. It is now generally believed that the diurnal S_1 (1, -2) mode, the semi-diurnal S_2 (2,2) and S_2 (2,4) modes in mid-latitudes are responsible for the generation of dynamo region electric fields which drive the normal S_q current system and the quiet time EEJ in daytime (Schieldge et al., 1973; Takeda et al., 1986). One of the interesting aspects of EEJ observed on some quiet days is the reversal of the normal eastward flow of current during morning (0500-0800 Local Time-LT) and evening hours (1400-1700 LT) as shown by the H component of the geomagnetic field decreasing below the nighttime level. This reversal of the normal eastward flow of current to westward current is given the name equatorial Counter Electrojet (CEJ) (Gouin, 1962; Gouin and Mayaud, 1967). It is well recognized that the equatorial sporadic E (E_{sq} irregularities) disappears with a decrease of the H field below its nighttime level (Hutton and Oyinloye, 1970; Rastogi et al., 1971; Krishna Murthy and Sen Gupta, 1972; Mayaud, 1977; Reddy, 1989 and Rastogi, 1989). Doppler frequency variations of the HF and VHF backscatter radar echoes from E_{sq} irregularities have been used to deduce the magnitude and direction of the EEJ electric fields during normal electrojet conditions (Fejer and Kelley, 1980; Reddy et al., 1987) and the reversed electrojet eletric fields during CEJ events (Crochet et al., 1979; Somayajulu and Viswanathan 1987; Somayajulu et al., 1993).

Apart from the detailed morphological characteristics of CEJ events studied with the help of ground based magnetometer records, attempts have been made, in the last two decades, to understand the physical processes underlying the phenomenon of CEJ events. Theoretical investigations to explain physical processes that generate CEJ events have proceeded on two different approaches. In one approach (Richmond, 1973; Reddy and Devasia, 1981, Anandarao and Raghavarao, 1987), it was suggested that the local interaction of height varying zonal winds with electrojet plasma can generate polarization electric fields which in turn can modify the latitudinal and height structure of the electrojet current. The detailed computations of Reddy and Devasia (1981) and Anandarao and Raghavarao (1987) have shown that EEJ current intensity (J) and the corresponding ΔH variations on the ground near the dip equator are very little affected by the local action of vertical shears of zonal wind. In a different approach, the possible reversal of the global eastward electric field (E_y) in the EEJ region due to abnormal combination of S_1 (1, -2), S_1(1,1), S_2(2,2) and S_2(2,4) tidal modes have been shown to produce a CEJ event in the late evening hours (Forbes and Lindzen, 1976a,b; Marriott et al., 1979; Hanuise et al., 1983). This calls for an identification of the abnormal combination of tidal modes and their variability which causes the CEJ event. Moreover, it is to be emphasized that the reversal of E_y should produce CEJ events on a much larger latitude extent than the electrojet latitudes. However, the most interesting aspect of the CEJ events is that the E_y reverses only at electrojet latitudes, over a limited longitude extent and is observed at the same local time when it occurs in different longitude sectors. Further, reliability of the theoretical wind models used to predict the observed variations in the H component during CEJ events have not been tested in the past for want of wind measurements in the equatorial mesosphere and lower thermosphere. With the advent of meteor wind radar (Reddi et al., 1991, 1993), partial reflection radar (Vincent and Lesicar, 1991) and Meteor Detection and Collection (MEDAC) system operating with Stratosphere-Troposphere (ST) radar, we now have measurements of mesosphere (Avery et al., 1990) and lower thermospheric winds at equatorial electrojet latitudes. In this paper, we present experimental evidence on the behavior of zonal and meridional winds, the amplitude and phase variations of tidal wind components observed with a Meteor Wind Radar (MWR) operating at Trivandrum during CEJ events observed in January and June months of 1987.

OBSERVATIONS

The study has been carried out using observations obtained simultaneously with a MWR, digital ionosonde and a fluxgate magnetometer operating at

Trivandrum (geographic latitude - 8.5°N, geographic longitude - 77°E, Dip - 0.5°N). The details of the meteor wind radar are given elsewhere (Raghava Reddy et al., 1992). The meteor wind radar operates at 54.95 MHz with a peak power of 40 kW and a selectable pulse repetition frequency of 300/400/500 Hz. The transmitter pulse width is 280 μs phase coded by a 28 bit pseudo-random code of bit length 10 μs which gives a range resolution of ±0.75 km. By using interferometer base line of 1, 3 and 10 wavelengths, the elevation and azimuth angle of arrival of meteor echoes were measured with an accuracy of ±1°. Consequently, the altitude of the meteor echoes could be measured with an accuracy of ±2 km. Identical five element Yagi-Uda antennas were used for both transmission and reception; the radar beam is oriented at an elevation angle of 45° and is switched alternately in the NE and NW azimuthal directions for acquiring data from a preset number of meteors from each azimuthal direction. The data recorded on a computer tape (CCT) from each meteor trail includes the time of occurrence of the echo, the pulse to pulse echo amplitude, slant range of the echo, Doppler frequency waveform and the phase differences between the echoes received at pairs of antenna elements of the interferometer system switched to the receiver sequentially from transmitter pulse to pulse. The quarter hourly ionograms were obtained from a digital ionosonde and the variation of the horizontal component of the earth's magnetic field (H) was obtained from a fluxgate magnetometer operated at Trivandrum.

DATA ANALYSIS

The meteor wind radar data obtained during January 19-31, 1987 and June 8-11, 1987 were analyzed to obtain the mean zonal winds and the tidal components. During the above recording period, the H component variations observed at Trivandrum show CEJ events on January 27-31, 1987 as well as on June 8-11, 1987. The period from January 19-26 was found to be free from counter electrojet effects during afternoon hours and hence these 8 days data is taken to represent the no-counter electrojet days for comparison with the five CEJ days data during the month of January. For June 1987 we did not have the corresponding no-counter electrojet days data for comparison. The time series data obtained from MWR at different altitudes are averaged at three hourly intervals (00-03, 03-06....21-24) and then the second version of the least squares fit method of Groves (1959) is adopted to obtain mean 3 hourly altitude profiles of the zonal and meridional winds (for details see Reddi et al., 1992). The zonal and meridional wind profiles thus obtained were taken to represent the mean profiles corresponding to the 3 hourly interval of an "equivalent counter electrojet day". The eight 3 hourly profiles of NS and EW winds were Fourier analyzed to obtain the mean winds and the amplitudes and phases of the diurnal, semi-diurnal and ter-diurnal components at one kilometer interval in the height range of 80-105 km. By using the same methodology, the data obtained during January 19-26, 1987 were analyzed separately to obtain the mean and the amplitudes and phases of the tidal components on the "equivalent no-CEJ days". Combining the data into three hourly bins was found necessary because the occurrence rate of meteors is low in the evening hours when the CEJ events are in progress. Further, at least 70-80 meteors distributed in the altitude region of 80-105 km are required to compute reliable wind profiles. However, in the morning hours, the number of meteors in the three hour bins will be about 450. The amplitudes of the tidal wind oscillations computed using 3 hourly average profiles result in underestimation of the diurnal component by 2%, semi-diurnal component by 5% and ter-diurnal component by 22.5%. The phases of the tidal components obtained, however, remain unchanged. It may be mentioned that because of the altitude variation of the occurrence rate of meteor trails, the accuracy of the measured winds vary with altitude and is about

2 m/s in the altitude range of 85-105 km. The above limitations inherent, in general, in the meteor wind radar data analysis do not affect the main conclusions of the present study.

RESULTS

Figs. 1 and 2 show the time variation of the horizontal component of the earth's magnetic field at Trivandrum during January and June months of 1987, respectively. The dashed curves in Figs. 1 and 2 are the variations of ΔH on quiet days without any counter electrojet effects. The nighttime baseline values for all the CEJ days and no-CEJ days were obtained by taking the average of the magnetic field values during 0000-0400 IST (IST is the India Standard Time corresponding to 82.5°E). The variations shown in the figures are above and below this baseline value. The necessary correction for D_{st} variation is also applied before determining the nighttime baseline values. It is to be noted that on January 28 and 29, 1987 (Fig. 1) the higher A_p values indicate disturbance effects superimposed over the CEJ effects. There are some major differences between the January and June events. They are:

(a) the intensity of the CEJ event defined as the maximum negative value varies from -50 nT to -10 nT during the month of January whereas, during June, it is about -10 nT to -20 nT;

(b) in the month of January, on CEJ days, ΔH reaches its maximum value around 1000 IST whereas the maximum occurs during 1100-1200 IST during June;

(c) the maximum intensity of the CEJ event is reached at about 1400-1500 IST during the month of January and shifts to 1600-1700 during June.

From a detailed examination of the quarter hourly ionograms recorded at Trivandrum, it is found that E_{sq} echoes are present in the ionograms from 0700-1700 on no-CEJ days whereas during CEJ days, E_{sq} echoes appear first around 0700 IST and then disapperar and reappear at different times of the day. In Figs. 1 and 2 the disappearance reappearance times of E_{sq} reflection in the quarter hourly ionograms recorded at Trivandrum are shown by an arrow and an inverted arrow respectively. It is seen that the disappearance of E_{sq} irregularities occurs at least 30-60 minutes before the ΔH goes down below the nighttime level and the reappearance of E_{sq} irregularities is also observed to occur 30-60 minutes before ΔH reaches its nighttime level.

Fig. 3 depicts the altitude variation of the mean zonal winds as obtained from the MWR during CEJ (full line) and no-CEJ days (dashed line) for January months. Fig. 4 shows the same for CEJ days in June. The background winds in January are westward at all heights during CEJ days. During no-CEJ days they are eastward from 90-100 km and marginally westward above 100 km. However, during June, on CEJ days, the mean zonal winds are weak and westwards below 85 km and eastward above 85 km.

The time variation of the zonal winds at different altitudes during CEJ days and no-CEJ days are shown respectively by a full line and by a dashed line, in Fig. 5 for January, 1987. The most outstanding feature to be pointed out in Fig. 5 is that the zonal wind velocity on CEJ days is westward at all heights from 0800-1800 IST, whereas, it is eastward from 1000-1600 IST on no-CEJ days. Further, in the morning hours of 0400-0800 IST, the zonal wind velocity is eastward on CEJ days up to 100 km and westward at all heights on no-CEJ days. Another interesting feature to be noted is that the westward zonal wind has a steady value of about 40-45 m/s from 1200-1400 IST, on CEJ event days. It is also to be noted that during 1400-1600 IST, when the CEJ events are in progress, the westward zonal wind velocity changes from 10 m/s at 96 km to about 60 m/s at 102 km. In contrast, the time variation of zonal wind shown in Fig. 6 for CEJ days during June behaves in a

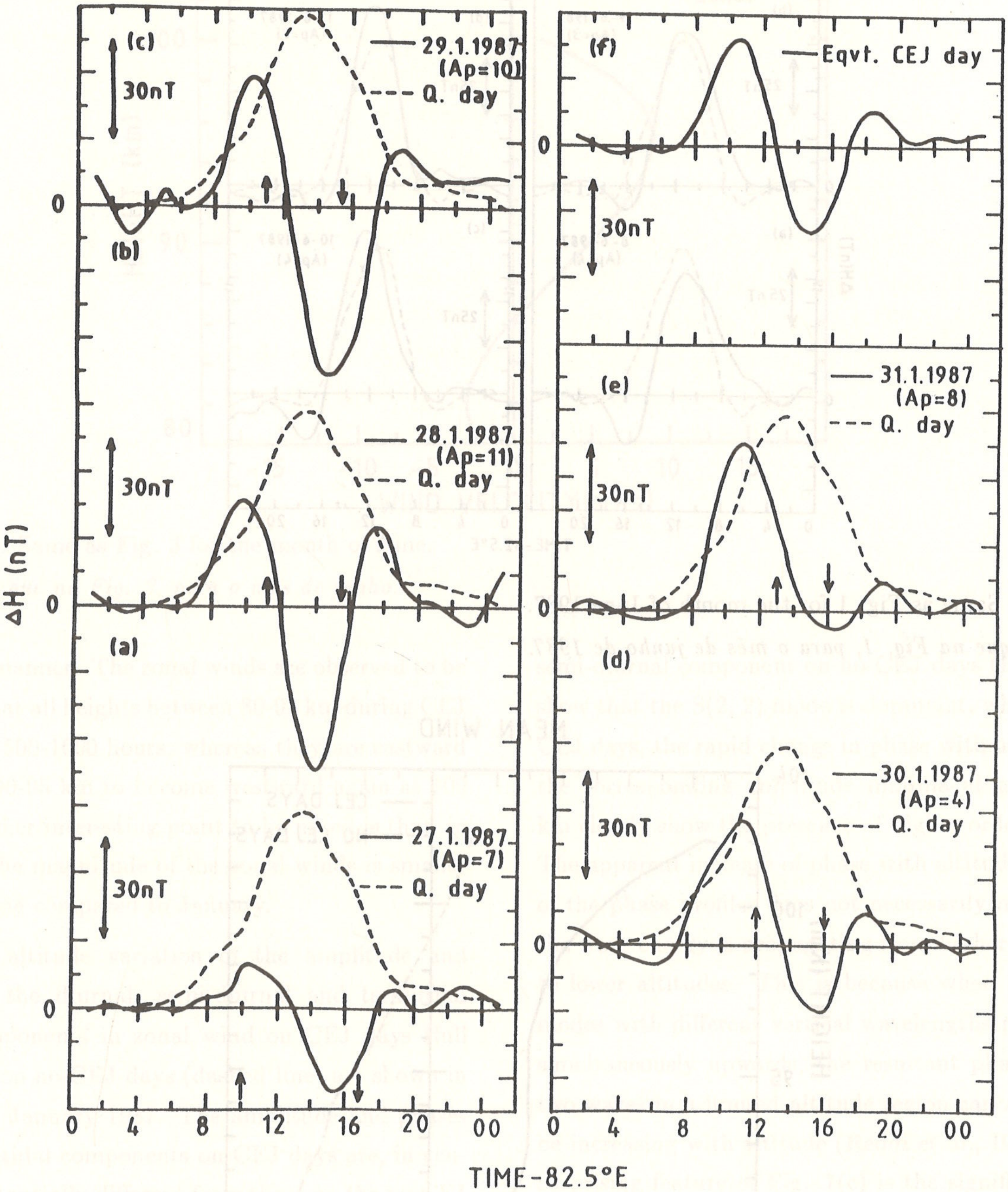

Figure 1. Time variation of the horizontal component (ΔH) of the earth's magnetic field during five counter electrojet days of January 1987 shown by full lines. The dashed curve shows ΔH variations on the quiet days which represent the normal S_q variations. Vertical arrow indicates the time of disappearance of E_{sq} and inverted arrow indicates the time of reappearance of E_{sq} irregularities.

Variação temporal da componente horizontal (ΔH) do campo magnético terrestre durante 5 dias de Eletrojato reverso em janeiro de 1987, mostrado em linha cheia. A curva tracejada mostra as variações de ΔH de período calmo representando as variações normais S_q. A seta vertical indica a hora de aparecimento e desaparecimento de E_{sq}.

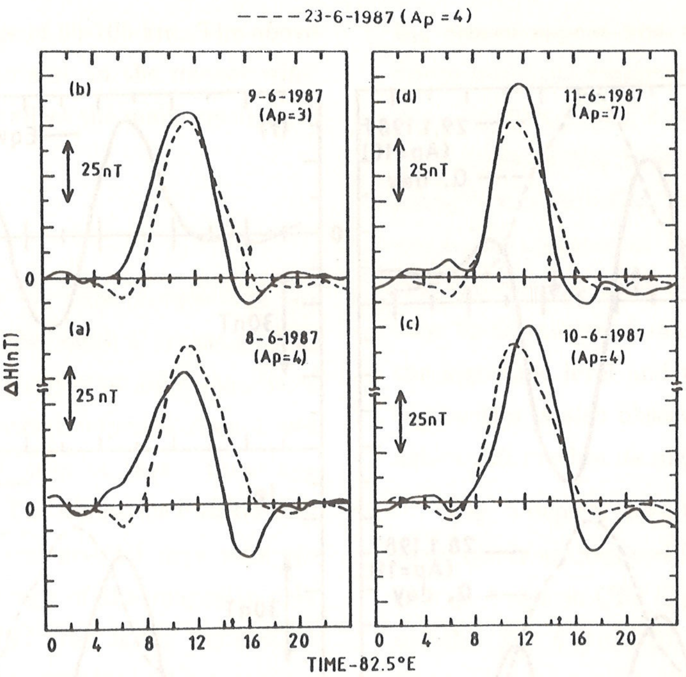

Figure 2. Same as Fig. 1 for the month of June 1987.

O mesmo que na Fig. 1, para o mês de junho de 1987.

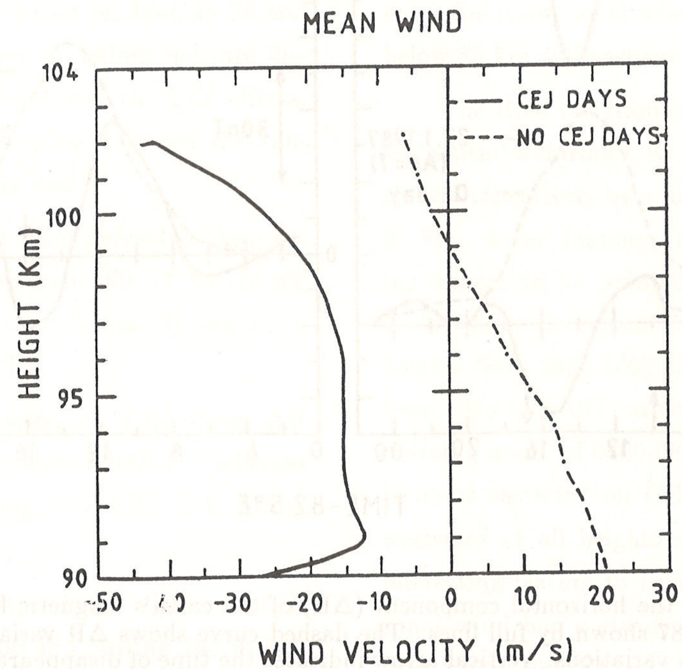

Figure 3. Height variation of mean zonal winds observed during CEJ days (full line) and no-electrojet days (dashed line). Eastward wind velocities are positive.

Variação com altura dos ventos médios zonais observados em dias de CEJ (linha cheia) e na sua ausência (linha tracejada). Velocidades de vento para leste são positivas.

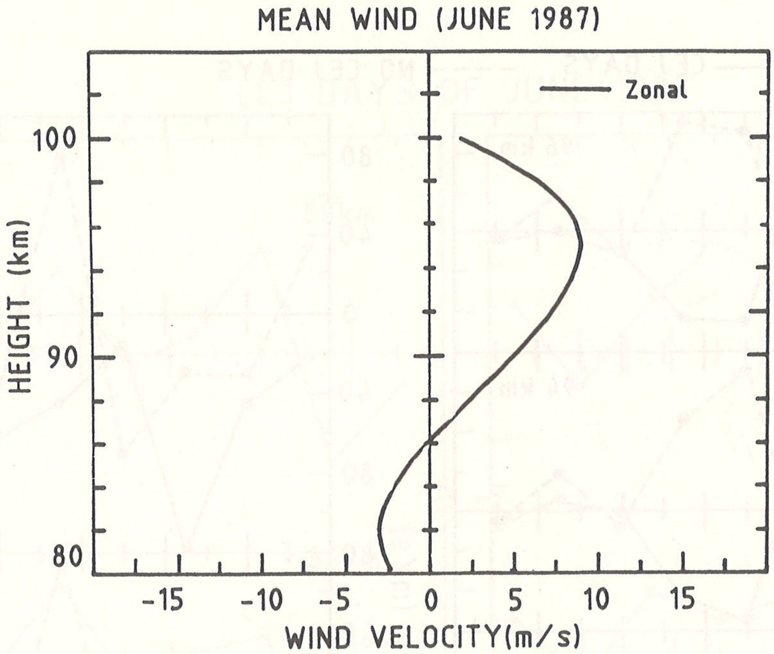

Figure 4. Same as Fig. 3 for the month of June.
O mesmo que na Fig. 3, para o mês de junho.

different manner. The zonal winds are observed to be westward at all heights between 80-90 km during CEJ times of 1500-1600 hours, whereas they are eastward between 90-95 km to become westward again at 100 km. Another interesting point to be noted is that, in general, the magnitude of the zonal winds is smaller during June compared to January.

The altitude variation of the amplitude and phase of the diurnal, semi-diurnal and terdiurnal wind components in zonal wind on CEJ days (full line) and on no-CEJ days (dashed line) are shown in Fig. 7 for January 1987. The amplitude and phases of all the tidal components on CEJ days are, in general, substantially different from those on the no-CEJ days. The important point to be noted is that the amplitude of the diurnal component is reduced on CEJ days compared to no-CEJ days (Somayajulu, 1988). The quasi-sinusoidal variation in the phase of the diurnal component on CEJ days (Fig. 7(a)) shows strong interference effects between two wave modes, possibly S_1 (1, 1) and S_1 (1, -2) while on no-CEJ days, the interference effects are not clearly discernible. In contrast, the amplitude and phase of the semi-diurnal component on no-CEJ days (Fig. 7(b)) show that the S(2, 2) mode is dominant, whereas, on CEJ days, the rapid change in phase with height and the corresponding amplitude minima at about 100 km clearly show the presence of higher order modes. The apparent increase of phase with altitude in some of the phase profiles does not necessarily mean that the wave energy is propagating from higher altitudes to lower altitudes. This is because when two wave modes with different vertical wavelengths propagate simultaneously upwards, the resultant phase of the two waves in a limited altitude region can appear to be increasing with altitude (Reddi et al., 1992). The surprising feature of Fig. 7(c) is the significant amplitude of the ter-diurnal component observed during CEJ days. This may be due to the generation of the ter-diurnal component through the non-linear interaction between the diurnal and semi-diurnal components. The phase jump observed at 100 km and the corresponding amplitude minimum of the ter-diurnal component on CEJ days may be due to the presence of more than one mode of both the diurnal and semi-diurnal components on CEJ days. The non-linear

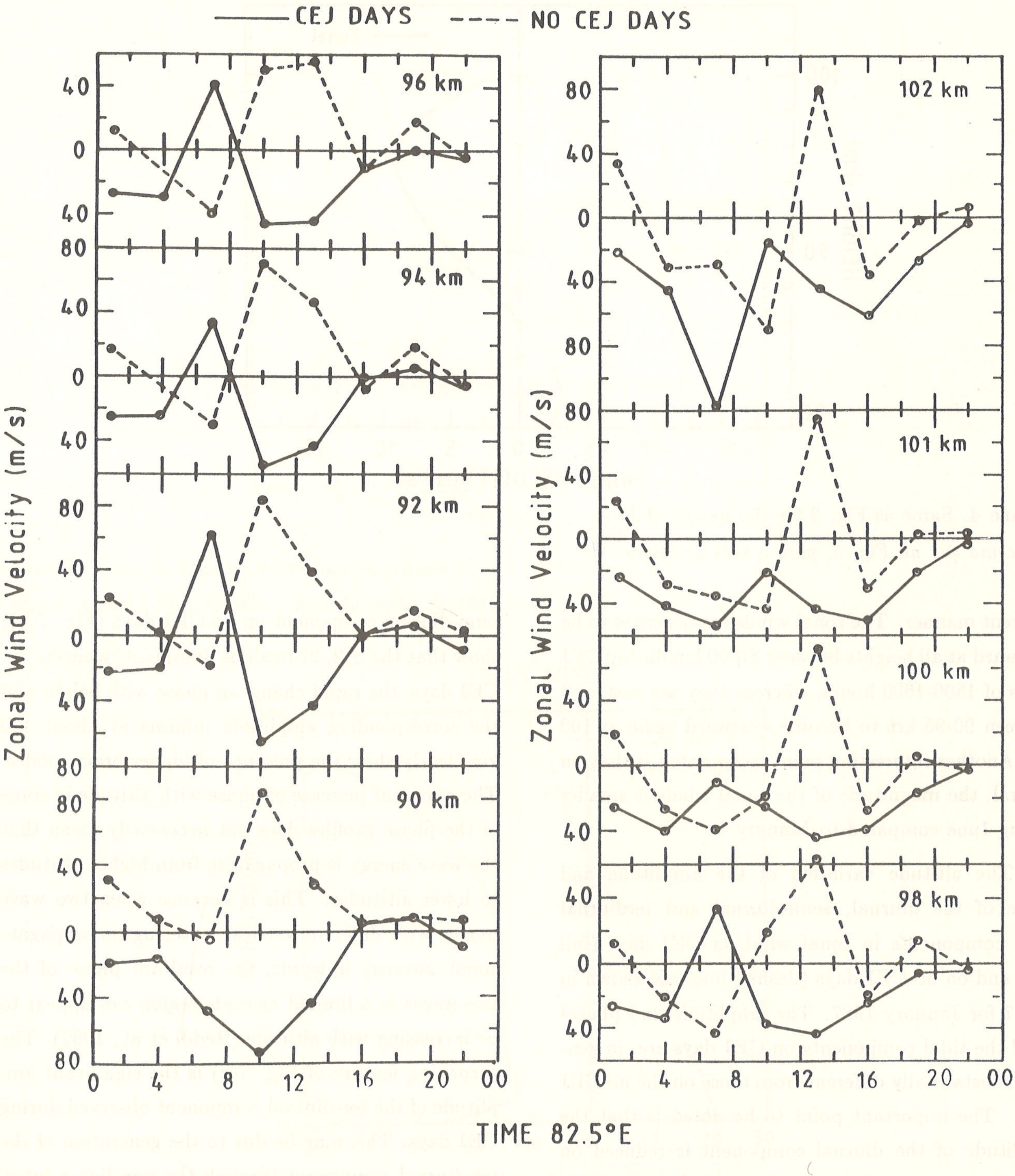

Figure 5. Time variations of the zonal wind velocity observed at different altitudes shown by full line on CEJ days and by dashed line on no-CEJ days of January 1987. Eastward wind velocities are positive.

Variação temporal da velocidade do vento zonal observado em várias alturas indicado por linhas cheias em dias de CEJ, e por linhas tracejadas na sua ausência, em janeiro de 1987. Velocidades de vento para leste são positivas.

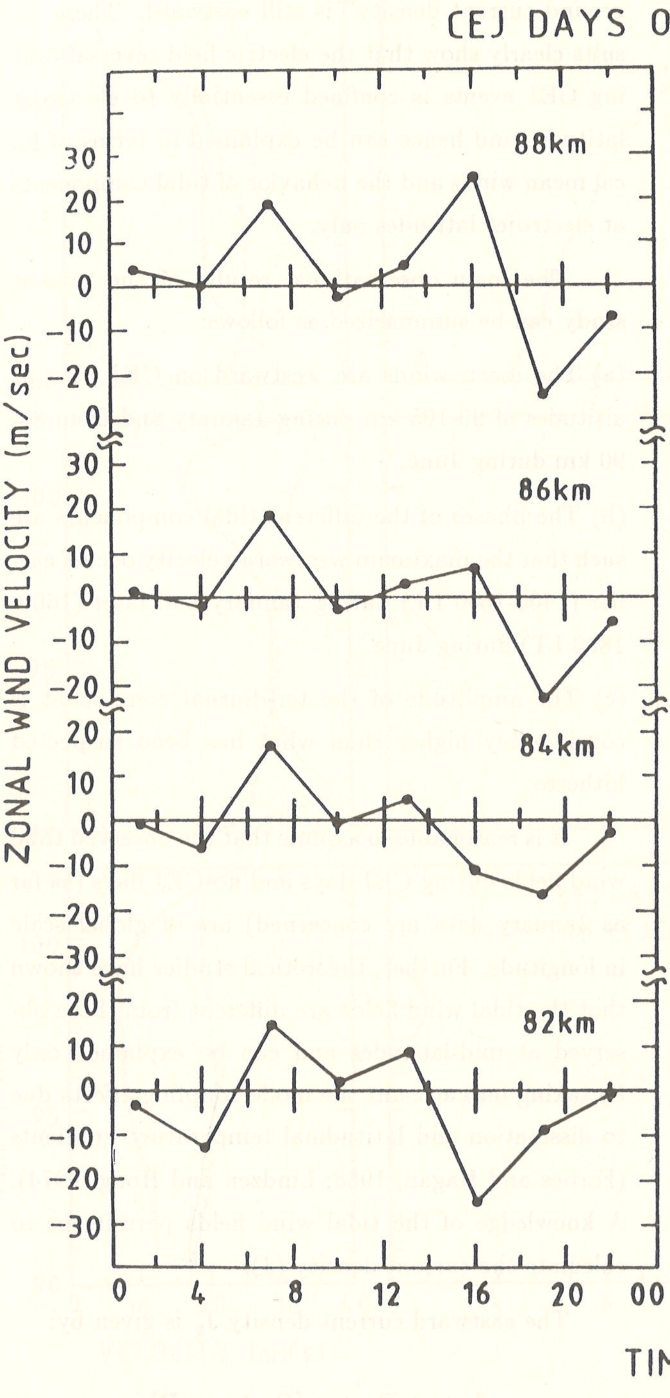

Figure 6. Same as Fig. 5 for CEJ days in the month of June 1987.
O mesmo que na Fig. 5, para o mês de junho.

interaction between the different diurnal and semi-diurnal tidal modes can result in the observed modulation in the amplitudes and phase of the ter-diurnal component. The amplitudes and phases of the diurnal, semi-diurnal and ter-diurnal components during CEJ days of June are shown in Fig. 8. It is seen that the amplitude of the ter-diurnal tidal component is higher compared to the diurnal and semi-diurnal components. However, at the time of westward maximum of the zonal wind in the evening hours all the three tidal modes could be in the westward wind phase producing a weak CEJ event.

DISCUSSION

It is generally believed that the dynamo region electric fields necessary to drive the global S_q current system and the normal daytime equatorial electrojet current system responsible for the observed surface magnetic field variations during daytime are produced by the first symmetric diurnal trapped mode S_1 (1, -2), the diurnal propagating mode S_1 (1, 1) and the semi-diurnal propagating modes S_2 (2, 2) and S_2 (2, 4) (Schieldge et al., 1973; Forbes and Lindzen, 1976a, b; Takeda et al., 1986). However, during CEJ events, the reversal of the electrojet current as seen from the decrease of the H component of the earth's magnetic field below the nightime level and the decrease being confined only to electrojet latitudes has focussed our attention on the possible large variabilities of mean winds and tidal wind components in the equatorial dynamo region. Forbes and Lindzen (1976a, b) have simulated CEJ events around 0600 LT and 1800 LT by assuming a change of tidal winds of 30-40% in amplitude and 1-2 hours in phase about their average values. On the other hand, Marriott et al., (1979), with an unusual combination of tidal wind components have shown the possible reversal of the east-west electric field (E_y), on a scale much larger than the EEJ. Furthermore, the detailed analysis of Fambitakoye and Mayaud (1976) showed that the enhanced part of the equatorial electrojet current is westwards during CEJ events whereas the "background current density" is still eastward. These results clearly show that the electric field reversal during CEJ events is confined essentially to electrojet latitudes and hence can be explained in terms of local mean winds and the behavior of tidal components at electrojet latitudes only.

The main observational results of the present study can be summarized as follows:

(a) The mean winds are westward on CEJ days at altitudes of 90-105 km during January and from 80-90 km during June.

(b) The phases of the different tidal components are such that the maximum westward velocity occurs earlier (1400-1600 LT) during January and later (1600-1800 LT) during June.

(c) The amplitude of the ter-diurnal component is considerably higher than what has been suspected hitherto.

It is reasonable to assume that the observed tidal wind fields during CEJ days and no-CEJ days (as far as January data are concerned) are of global scale in longitude. Further, theoretical studies have shown that the tidal wind fields are different from those observed at mid-latitudes and can be explained only by taking into account the mode coupling effects due to dissipation and latitudinal temperature gradients (Forbes and Hagan, 1988; Lindzen and Hong, 1974). A knowledge of the tidal wind fields permits us to calculate the current density (J).

The eastward current density J_y is given by:

$$\mathbf{J}_y = \sigma_1 \mathbf{E}_y + \sigma_2 [\mathbf{E}_z + \mathbf{u} \times \mathbf{B}]$$

where σ_1 is the Pedersen conductivity, σ_2 is the Hall conductivity, E_y is the dynamo east-west electric field, $\mathbf{E}_z$ is the vertical polarization field, $\mathbf{u}$ is the zonal wind and $\mathbf{B}$ is the geomagnetic field. The zonal wind velocity of about -45 to -50 ms^{-1} with appropriate height gradient observed during CEJ events

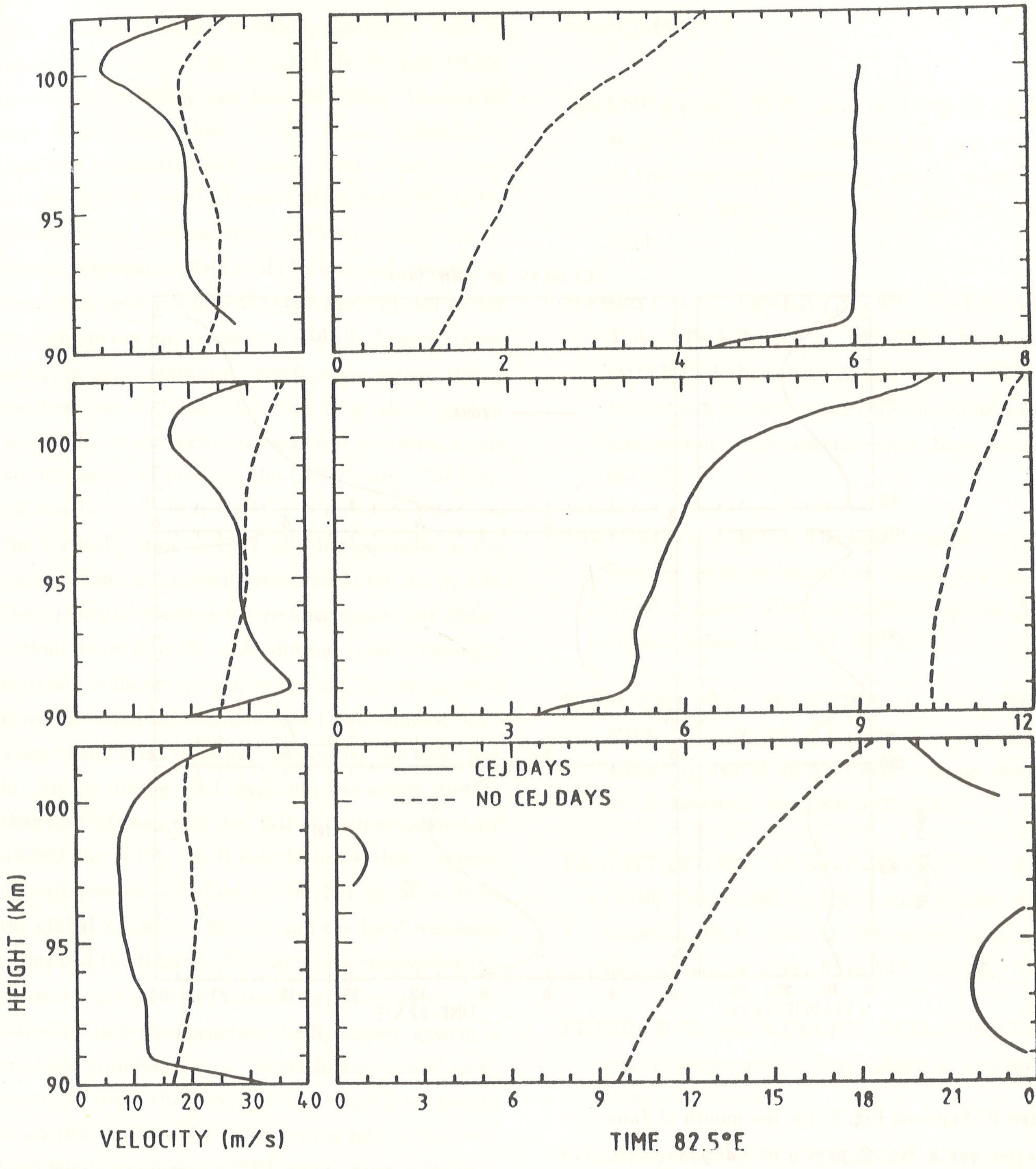

Figure 7. Altitude variation of the amplitude and phase of the diurnal (a), semi-diurnal (b) and ter-diurnal (c) winds in the meteor region over Trivandrum during CEJ events (full line) in January, 1987 and no-CEJ days (dashed line). The times correspond to the observed eastward velocity maximum.

Variação com altura da amplitude e fase das componentes de período 1(a), 2(b), e 3(c) dos ventos na região de meteoros em Trivandrum durante eventos de CEJ (linhas cheias) do mês de janeiro de 1987 e em sua ausência (linhas tracejadas). O tempo corresponde ao máximo da velocidade para leste.

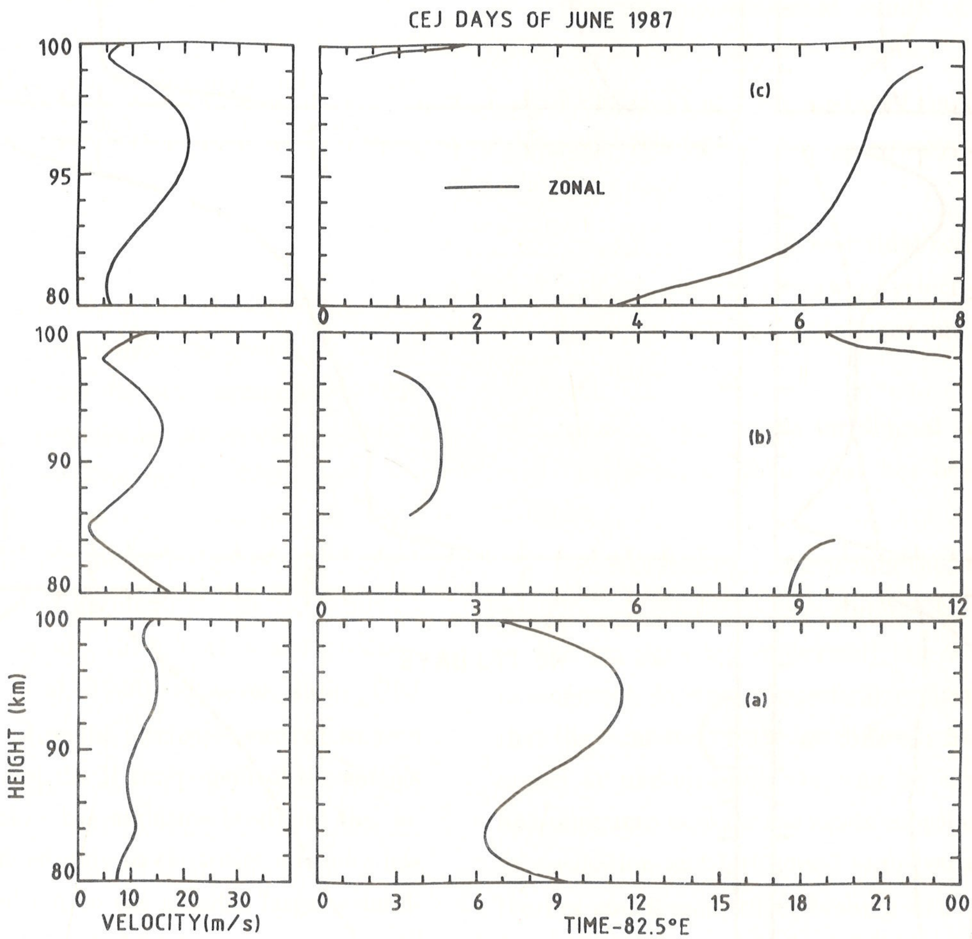

Figure 8. Same as Fig. 7, for the month of June.

O mesmo que a Fig. 7, para o mês de junho.

can generate a local vertical polarization field of about 1.5 - 2.0 mV/m directed downwards (Richmond, 1973; Reddy and Devasia, 1981; Anandarao and Raghavarao, 1987). The vertical polarization field due to global scale S_q fields could be less in magnitude than the vertical polarization fields due to local winds and directed upward. Consequently, the effective polarization field could be directed downwards during an eastward current as indicated by ΔH values reaching below nighttime level and the disappearance of E_{sq} in the ionograms. Therefore, we suggest that a combination of global tidal wind fields which tend to weaken E_z in combination with local westward winds are necessary to produce the CEJ events. The logical conclusion is that while it is probably true that the vertically trapped $S_1(1, -2)$ diurnal mode in the mid-latitudes is primarily responsible for the S_q and the equatorial electrojet current systems, our observations show that the semi-diurnal tidal component certainly influence the generation of CEJ events. This is corroborated by the pronounced semi-diurnal character of the ΔH variation shown by the full line in Fig. 1 during CEJ days and the nearly diurnal character of the quiet day ΔH variations (shown by dashed line in Fig. 1). It is to be noted that a correct quantitative contribution to the ΔH variation from the global S_q current system and the local westward winds and the tidal wind components observed at the equator is not possible, unless information about mid-latitude winds that generate the S_q current system is available simultaneously. Nevertheless, model computations using the observed tidal wind fields should be carried out in order to assess the role of observed local winds producing a CEJ event. Such a study is contemplated by the authors. In conclusion, the observed features of the mean zonal winds, the altitude variations in amplitude and phase of the tidal wind components at low latitudes represent the first direct evidence of the role played by the tidal components during CEJ events observed at the equator.

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